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Dynamic Analysis of A Towed Cable-Body-Array System

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Abstract

Towed systems widely used in ocean engineering applications, essentially consists of flexible lines connected to rigid bodies. In this paper, an attempt has been made to examine the dynamic response of flexible lines used in the marine environment using special purpose software Orcaflex. The different loading conditions generally encountered such as wave, underwater currents and platform motions are considered and these loads are extremely complex and time varying. This geometric nonlinear problem involving large deformations of the flexible are solved by finite element method using an explicit time domain integration scheme. The flexible lines are modelled as lumped masses connected by massless springs and the vessel or buoys are modelled as rigid bodies. A basic understanding of the dynamics of the flexible and their modeling are summarized in this paper by presenting a typical class of problem which includes the dynamic response of towed arrays deployed from a moving vessel. It is concluded that for towed arrays, relatively small variations (upto 10%) in neutral buoyancy of an array can lead to large variations (upto 40m) in the operating depth..

Introduction

The underwater towing of flexible cylindrical structures belongs to the class of fluid structure interaction problems commonly referred to as “cylinders in axial flow”. Towed flexible arrays are extensively used in military, paramilitary and civilian applications. In the military application, a neutrally buoyant flexible cylinder is towed from a ship or submarine using a tow cable. This structure is essentially an acoustic array or antenna, which contain transducer for the detection of underwater targets. In paramilitary applications, these types of structures are used for coastal surveillance and patrolling of offshore installations. The civilian uses are in geophysical explorations for seismic prospecting. In all these applications, tow cable plays an important role, in electrical signal transmission as well as for withstanding the hydrodynamic forces. A typical towed cable-body-array configuration consists of a towed cable, towed body, a flexible array and a tail rope connected in series. The array is a cylindrical tube in which a series of transducers are housed. The deployment depth of such neutrally buoyant array is controlled by appropriate payout of the tow cable from a winch and the tow speed of the vessel.

Modern requirements for deep towing often necessitate the use of cables, for example Holmstrom [1] describes a system deploying 9000m of cable. The operator faces the problems of handling huge quantities of cable and also the difficulties in locating and steering the underwater vehicle over a specified course. Jeffrey Ketchman and Lou [2] describe a two dimensional simulation that is notable in several aspects. The paper describes the influence of bending stiffness for a towed cable. Albow and Schechter [3]carried out the simulation of a towed array. They assume a Hooke's law stress strain relationship and conducted studies on the hydrodynamic behaviour. Andrew and Bull[4] have conducted studies on towed array hydrodynamic behaviour such as drag, steady towing configuration and transient responses to the speed and course changes. Theodoracatos and Calkins [5] reported experimental studies of the hydrodynamics of the towed flexible cylinders aided by video image processing. The experiments were conducted in a towing tank. Chapman [6] proposed a model to describe the dynamic behaviour of an underwater towed system. The model is mainly used to simulate the behaviour when the towing ship travels in a circular trajectory and is not fully three dimensional.

Scope of Work

Theobjectives of the paper comprise of:

1. modeling and simulation of flexible lines in marine environment using a fully three dimensional finite element model.
2. static and time domain simulations of flexible lines subjected to wind, wave, drag, inertia, elastic forces and time varying loads is carried out using non linear time domain finite element model. A typical towed array system is constructed in terms of modules, which may differ in size and weight. The neutral buoyancy of a towed array has to be ensured during the array assembly. Different modules of the towed array are weighed during the assembly and the mass distribution of the array has to match the weight of water displaced to ensure neutral buoyancy. In practice, the mass of the array is controlled by the electronic components and other mechanical sub-assemblies such as electronic modules, mechanical spacers, inter-connecting wires, electro-mechanical connectors and the filler fluid. The assembled array tends to become either negatively buoyant or positively buoyant and the usage of such arrays under towed condition leads to affect its functional performance. The effect of non-neutral buoyancy of a typical towed array system is examined briefly in this paper.

Methods of Analysis

The methods of analysis are the most important part of the design process. A variety of options are available due to the recent advances in the computational mechanics.

The first option is to use a static analysis. One rule of thumb is that dynamic amplification becomes important when the period of the system is larger than two seconds. Even the structures analysed statically will require some dynamic consideration to analyse the effect of fatigue. If the inertia forces are comparatively important, dynamic analysis is used and two possibilities exist. They are the frequency domain approach and the time domain approach. In the frequency domain approach, the transient effects are neglected and it concentrates on steady state solutions. The method assumes a linear system. The system is analysed in the time domain by some step technique, in which case transient effects may be considered as well as nonlinearities. A transient process is defined as a time dependent variation in behaviour, of limited duration , spanning between two steady states of much longer duration. One or both of the steady states can be periodic or in the limit constant, in time. The duration of the transient may be of the order of seconds, as during an earthquake, or of hour or days, as during an ocean storm.

Brief Description of The System

The definition sketch of a typical towed cable-body-array system is shown in Fig.1. It consists of an electro-mechanical heavy cable (HC), a towed body (TB), a light cable (LC) and the towed array modules followed by a segment which is a tail rope. A typical towed system uses tow cable of length which vary from 100m to 1000 m, a neutrally buoyant cable of length 100m to 500 m, array of length 50m to 200 m, followed by a tail rope of length 10m to 30 m. The diameter of tow cables vary from 20 mm to 40 mm and that of array vary from 60 to 90 mm.

The vertical and horizontal distances (Y and X in Figure) are called the Depth and the Trail of the body respectively. The array is a circular cylinder made of polyurethane or PVC tube with a stress member running along the length of the tube to take the axial force arising from the hydrodynamic drag. The stress member is usually a ‘Kevlar’ rope. Further the array contains a bundle of electrical wires and a suitable filler fluid to make it neutrally buoyant under submerged conditions. The downstream end of the array is connected to a Drogue or a tail rope, which provide the necessary tension to keep the array free from any undulations.

The different segments that contribute for the magnitude of line tension build up due to steady state hydrostatic and hydrodynamic forces at various interface joints are briefly described.

- **Towed Body (TB) :** It is a negatively buoyant body connected to a heavy cable of 32mm diameter by an U-shaped tow bridle at the fore end. The two ends of the bridle are connected to the pivot axis which passes through the geometric centre of towed body. The body is elliptical in cross section.
- **Light Cable (LC) :**It is a neutrally buoyant flexible cylindrical structure of length 600m and diameter of 32mm connected between the linear array modules at one side and to the aft side of the towed body at other end.
- **Array modules:** Array modules consist of nine numbers and these are connected to LC at one end and to a tail rope at the aft end. The overall length of array modules and diameter are 210m and 80mm respectively.

- **Tail rope:** It is a polypropylene rope of length 30m and diameter 32mm connected to the aft end of array module and designed to provide a certain minimum hydrodynamic drag which is essential during deployment & recovery operation of the system.

Numerical Simulation of The Cable

The hydrodynamic model is usually composed of two parts; the cable and the towed body. The equations of motion for the cable and the towed body are nonlinear and their dynamic behaviours during various operations are mutually dependent. As a result, these equations are strongly coupled. In order to study the complete problem, they must be solved simultaneously as a whole. It is not easy to solve such a complicated problem analytically and numerical methods are usually employed.

The most prevalent approaches used nowadays in determining the hydrodynamic performance of a cable in an underwater towed system are the lumped mass method and the finite difference method. However, the explicit time domain integration scheme used in the lumped mass method made the method conditionally stable. In this method, the cable is discretized at the very beginning of modeling and replaced by point masses joined together by massless elements of finite lengths. The resulting governing equations lead to a set of ordinary differential equations derived directly from Newton’s Law of motion, which can be solved by various numerical algorithms. The collapse of the numerical procedure at large time steps in the method is not due to the instability of the numerical scheme, but is caused by the failure of the Newton-Raphson iterative procedure which is used to solve the nonlinear equations of motion.

The lumped mass method has the following advantages.

1. Straightforwardness: the modelling and the mathematical formulation has clear physical interpretation.
2. Economy: a moderate amount of computational time is needed.
3. Versatility: simple as it is, the method can solve many different types of problems including those of non linearity, unsteady state, non uniform cable and oscillatory current.

Hydrodynamic Forces

The hydrodynamic resistance is the subject of extensive study for its importance as a force resisting any imposed motion and for complex phenomena that cause it, depending upon the application the towed cable that may be either vertical or nearly horizontal as in the case of towed arrays. The dynamic behaviour of tow cable in water is affected primarily by the presence of non-linear drag force. The hydrodynamic forces are completely different in these two cases. In the first case, there is a strong resistive in-line force and vortex induced out of plane force causing out of plane oscillations. In the second case, force is primarily inviscid and acts under certain condition to destabilize the motion of the cable.

The hydrodynamic forces on a flexible cylinder exerted by a fluid in steady motion relative to the cylinder can thus be represented in terms of elemental components of drag, normal and tangential to the cylinder along its length. It is also possible to express the components drag as a function of corresponding normal and tangential components of velocity of fluid relative to cylinder, according to resistance law. The application of law of resistance for a component of velocity normal to the surface obstructing the stream is established and demonstrated by experiments. Though the properties of drag coefficient for fluid flow that is normal to a circular cylinder are well established but the nature of tangential drag coefficient in relation to tangential flow along the length of horizontal circular cylinder has not received much attention.

Some theoretical and experimental studies have been carried out to characterize turbulent boundary layer growth on long slender axisymmetric studies. White (1972) based on the observations of Rao (1967) carried out computation of skin friction coefficient and boundary layer growth parameters for turbulent flow past long cylinders. The following curve fit approximation to calculate skin friction and total drag were reported which is the basis of estimate of drag coefficient for long and smooth circular cylinders in axial flow. In this application

$$C_{TA} = 0.0015 + (0.30 + 0.015\,(L/a)^{0.4})\,Re_L^{\{-1/3\}} \qquad \ldots(1)$$

For $L/a < 10^6$, $10^6 < Re_L < 10^9$

In this equation, L is the length of cylinder and a its radius. The above formulae were tested against the available experimental data by White (1972) which showed an error of 9%. This is the lowest for any known theory and these formulae can be used to estimate the drag force on a long flexible cylinder in axial flow.

Based on an experimental study on the transverse motion of long flexible cable with free downstream end in axial flow, Hansen and Ni (1979) obtained an empirical relation for drag coefficient for tail rope

$$C_{TR} = 0.4\,[UD/2\,v]^{\{-0.4\}} \qquad \ldots(2)$$

In this expression, U is the velocity, D is the diameter and v is the kinematic viscosity. This expression can be used for estimating frictional drag forces on a cylinder with rough exterior surfaces. According to Kennedy (1987) for small angles of attack less 3 deg, a normal component of fluid velocity does not exist or its no longer causing a pressure difference across the cylinder and hence hydrodynamic drag may be thought of as being caused by the frictional force only. Hence in this analysis the segments tail rope, array hose modules and LTC are assumed to be axial to the flow and tangential drag coefficient has been evaluated based on equations (2) and (1).

Based on empirical relation proposed by Hoerner (1956), the drag force on the elliptical body was estimated using the relation

$$C_{DB} = C_{f\,turb}[\,4 + 2\,(c/t) + (t/c)^2\,] \qquad \ldots(3)$$

Where c and t are the major and minor axis of elliptical section. The frictional coefficient due to turbulence is assumed to be 0.005 in the present case as estimated from Hoerner (1956). This relation does not account for any control surfaces and hence another 25% was added to obtain a realistic value of the complete drag coefficient.

$$\text{Drag force} = C_{TR}\tfrac{1}{2}\ \rho\ V^2 \pi\ D_R\ L_R + C_{TA}\ \tfrac{1}{2}\ \rho\ V^2\ \pi\ D_A\ L_A + C_{TC}\ \tfrac{1}{2}\ \rho\ V^2\ \pi\ D_C\ L_C \quad \dots (4)$$

C_{TR}= Coefficient of tangential drag for rope, C_{TA} = Coefficient of tangential drag for array All the above equations (1) to (4) have been used for estimation of hydrodynamic drag forces namely array module, LC, tail rope and elliptical towed body.

Cross Flow Principle

Lines are flexible linear elements used to model cables, hoses, chains or other similar items in Orcaflex. The line is divided into a series of line segments which are then modeled by straight massless model segments with a node at each end. The model segments only model the axial and torsional properties of the line. The other properties like mass, weight, buoyancy etc are all lumped to the nodes. The drag forces applied to a line are calculated using the Cross flow principle. That is, the fluid velocity relative to the line is split into its components Vn normal to the line axis and Vz parallel to the line axis. The components of drag force normal to the line axis are then based on Vn and its x and y components Vx, Vy. The component of drag force parallel to the line axis is based on Vz.

$Fx = P.(\tfrac{1}{2}.\rho.(Dn.L).Cdx.Vx.|Vn|)$
$Fy = P.(\tfrac{1}{2}.\rho.(Dn.L).Cdy.Vy.|Vn|)$
$Fz = P.(\tfrac{1}{2}.\rho.(\pi Da.L).Cdz.Vz.|Vz|)$
Fx, Fy, Fz = Drag force components in local line directions.
P = proportion wet
P = fluid density
Dn.L = Drag area normal to the line axis
πDa.L = Drag area in the axial direction
Cdx, Cdy, Cdz = Drag coefficients in x, y and z directions

Selection of Time Step

For efficiency of computation, Orcaflex uses two integration time steps in the dynamic simulation an inner time step and a larger outer time step. Most calculations during the simulation are done every inner time step, but some parameters like hydrodynamic forces are only recalculated every outer time step. Both time steps must be short enough to give stable and accurate simulation. The inner time step should not exceed 1/10 th to 1/20 th of the shortest natural period of motion for any degree of freedom in the model. The shortest natural period is reported after static analysis is completed.

Assumptions

- The flow is steady and uniform throughout the various sections.
- The flow is fully developed and under turbulent regime for all the tow speeds.

- The sum of all external forces due to various modules are lumped at the geometric centre of towed body.
- LC, Array module and Tail rope are neutrally buoyant.

The physical properties of the different sections of the array are shown below

Analysis

The steady state configuration of the system has been determined using an explicit time domain simulation using beam element. This involves equilibrium of hydrodynamic, hydrostatic, inertial and elastic forces acting on various parts of the system for a given ship speed using finite element method. The analysis provides the axial force of the towed cable array system along their length, and the geometric position of the array at different tow speeds. The weights of the array modules are given as an input for the system. The steady state configuration and the nodal loads obtained for different ship speeds. The method used for the steady state analysis is based on an explicit time domain method and takes into account the variations in the neutral buoyancy of array modules.

Results and Discussion

In this study, a typical towed cable-body-array system is chosen, whose physical properties are given in Table 3. The boundary conditions for the towed system is assumed as fixed to an on board winch and free at its downstream end. A typical cable payout of 100 m is selected for the study. The towed body considered is a negatively buoyant body attached at the end of the heavy cable.

A towed array generally consists of different modules and lengths and is having varying weight distribution. The neutral buoyancy of a towed array is required to be ensured during the array assembly. Different modules of the towed array are weighed during the assembly and the weight of the array has to match the weight of water displaced to ensure neutral buoyancy. Table 4 shows the typical values of the towed array with percentage variations in the weight distribution considered for the present study.

The ship velocity is given as an input and the steady state configuration is obtained for a few selected operating speeds namely 6,8,10 & 12 knots. The results obtained are shown in the Table 5.

From the results it is found that the cable tension increases with the increase in the tow speed. The depth decreases with increase in the tow speed. It is also clear that making the array negatively buoyant has an effect on depth, tension and horizontality.

For a perfectly neutrally buoyant array and light cable, the depth of the towed body and the array remains same. The effect of variation in the depth keeping characteristics of the non-neutrally buoyant array with different ship speed is shown in Table 6. It is seen from Table 5 that the non-neutral buoyancy of the array drastically changes the operating depth of the array at lower speeds. The end A of the array is at a depth of 13 m from the towed body where as the end B is at as depth of 22 m from the towed body at 6 knots.

The depth difference between the two ends of the array is 9 m at 6 knots, which reduces to 6 m at 12 knots. Thus marginal changes in the weight (up to 15%) of array can lead to large changes in the operating depth when used along with a long neutrally buoyant cable. The difference in operating depth is predominant at lower tow speeds and tends to neutralize at higher speeds.

The time domain simulation is done for the neutral buoyancy of the array for different operating speeds and the results are shown in table 7.

It is inferred that the alignment of the towed body and array remains almost horizontal. That means the depth of the towed body and the array remains the same. The tension increases with increase in tow speed.

The combined action of wind and wave is described by a sea state number which can vary from 0 to 9. The simulation was done for two different sea states like sea state1 and sea state 2 for each speeds like 6 knots and 8 knots. The corresponding wave height and wave period of the two sea states are shown in Table 8.

The result is shown in Table 9

The transient variations in tensions for sea state 1 & 2 are nearly 1 % and 6% of the mean value for the given configuration. At lower tow speeds there is difference in the operating depth and tends to neutralize at higher speeds.

Results and Conclusion

A commercial explicit time domain code ‘Orcaflex’ is used for modeling the flexible towed array system and the effect of variation in the neutral buoyancy on the depth keeping characteristics of a towed array is studied. The difference in operating depth due to the non-neutral buoyancy of the array predicted by the explicit scheme using the software fairly agrees with the values observed during the hydrodynamic trials. The transient tensions at different locations of the array and cable are also found to match with the values observed from trials. The exercise reveals the criticality and importance of neutral buoyancy in a towed array.

In the case of towed arrays, relatively small variations (upto 10 %) in neutral buoyancy of an array can lead to large variations in the operating depth. The difference in operating depth due to the non-neutral buoyancy of the array predicted by the analysis is consistent with the values recorded during the hydrodynamic trials. The steady state tensions at different positions of the array and cable are also found to agree with the values observed from trials. The transient variations in line tensions for sea state 1 and 2 are nearly 1% and 6% of the mean value for the given configuration respectively.

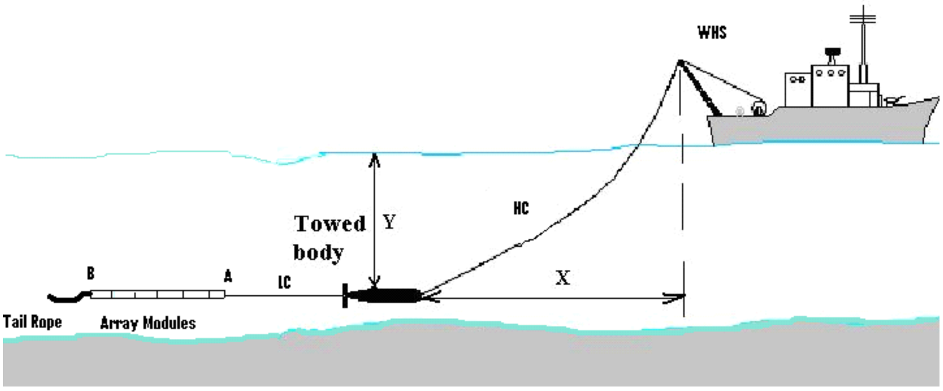

Figure 1: Definition sketch of a towed cable-body-array system

Table 1: Physical properties of the different modules of the array

Modules	Length in metres	Mass per unit length (tonne/m)
1	25	0.0056
2	11.5	0.0059
3	12.7	0.0058
4	33.5	0.0052
5	21.6	0.0054
6	33.5	0.0052
7	12.7	0.0058
8	25	0.0056
9	35.2	0.0049

Table 2: Physical and hydrodynamic properties of the towed body and the tail rope

Properties	Towed body (TB)	Tail rope
Mass (tonne)	0.32	0.028
Volume (m^3)	0.07	0.02
Height (m)	1.3	0.032
Drag area in X direction (m^2)	0.4	3.52
Drag area in Y direction (m^2)	0.9	1.12
Drag area in Z direction (m^2)	0.2	1.12
Drag coefficient in X direction	0.5	0.01
Drag coefficient in Y direction	1	0.01
Drag coefficient in Z direction	1.1	0.001

Table 3: Geometric, Elastic and Hydrodynamic properties of the cable and array

Properties	**Heavy Cable (HC)**	**Light Cable (LC)**	**Array**
Length (m)	100	630	210
Diameter (m)	0.032	0.032	0.08
Mass per unit length (tonne/m)	0.0042	0.00082	Varies for each modules
Bending stiffness (kNm^2)	0.2	0.1	0.01
Axial stiffness (kN)	3130	1500	10
Torsional stiffness (kNm^2)	0.4	0.2	0.01
Normal drag coefficient	1.2	1	1
Axial drag coefficient	0.01	0.003	0.003

Table 4: Typical percentage variation in weight of array modules from neutral buoyancy

Array modules from end A	1	2	3	4	5	6	7	8	9
Length (m)	25	11.5	12.7	33.5	21.6	33.5	11.5	25	35.2
% of variation from neutral buoyancy	+8.3 %	+15.3 %	+13.4 %	+2%	+5%	+2%	+13.4 %	+8.3 %	-4.6%

Table 5: Tension at different locations in the array modules

Tension at various locations	**6 knots**	**8 knots**	**10 knots**	**12 knots**
Tension at end A of HC (kN)	6.72	9.69	14.02	19.51
Tension at end B of HC (kN)	4.94	7.89	11.95	17.01
Tension at end A of LC (kN)	0.01	0.01	0.08	0.01
Tension at end B of LC (kN)	0.81	1.41	2.17	3.04
Tension at 655m from LC (kN)	0.71	1.23	1.89	2.71
Tension at 666.5m from LC (kN)	0.65	1.15	1.79	2.55
Tension at 679.2m from LC (kN)	0.6	1.07	1.63	2.33
Tension at 712.7m from LC (kN)	0.54	0.88	1.35	1.95
Tension at 734.3m from LC (kN)	0.43	0.73	1.14	1.57
Tension at 767.8m from LC (kN)	0.29	0.51	0.78	1.12
Tension at 780.5m from LC (kN)	0.24	0.41	0.64	0.91
Tension at 805.5m from LC (kN)	0.15	0.24	0.39	0.56
Depth of TB (m)	46.68	34.23	26.5	21.2

Table 6: Effect of non neutral buoyancy on operating depth

Depth(m)	6 Knots	8 Knots	10 Knots	12 Knots
Towed body depth (m)	47	34	26	21
Depth of array - end A (m)	60	47	38	32
Depth of array - end B (m)	69	54	45	38

Table 7: Tension at various locations of array modules

Tension at various locations	**6 knots**	**8 knots**	**10 knots**	**12 knots**
Tension at end A of HC (kN)	6.63	9.61	13.98	19.44
Tension at end B of HC (kN)	4.83	7.803	11.92	16.99
Tension at end A of LC (kN)	0.023	0.021	0.021	0.024
Tension at end B of LC (kN)	0.705	1.356	2.12	3.09
Tension at 655m from LC (kN)	0.678	1.193	1.844	2.71
Tension at 666.5m from LC (kN)	0.642	1.14	1.736	2.495
Tension at 679.2m from LC (kN)	0.59	1.031	1.63	2.33
Tension at 712.7m from LC (kN)	0.49	0.868	1.356	1.84
Tension at 734.3m from LC (kN)	0.407	0.705	1.085	1.627
Tension at 767.8m from LC (kN)	0.28	0.488	0.705	1.085
Tension at 780.5m from LC (kN)	0.226	0.38	0.651	0.922
Tension at 805.5m from LC (kN)	0.136	0.235	0.325	0.488
Depth of TB (m)	46.75	34.23	26.24	20.95

Table 8: Wave height and wave period for different sea states

Sea state	**Wave height in metres**	**Wave period in seconds**
1	0.11	3
2	0.85	5

Table 9: Effect of variation of tension and depth for different sea states

Tension at various locations	**6 knots sea state1**	**6 knots sea state2**	**8 knots sea state1**	**8 knots sea state2**
Tension at end A of HC (kN)	6.81	7.134	9.77	10.15
Tension at end B of HC (kN)	4.99	5.208	7.94	8.264
Tension at end A of LC (kN)	0.012	0.019	0.008	0.015
Tension at end B of LC (kN)	0.835	0.855	1.41	1.44
Tension at 655m from LC (kN)	0.734	0.75	1.24	1.266
Tension at 666.5m from LC (kN)	0.676	0.694	1.157	1.175
Tension at 679.2m from LC (kN)	0.622	0.635	1.058	1.076
Tension at 712.7m from LC (kN)	0.515	0.526	0.868	0.886
Tension at 734.3m from LC (kN)	0.43	0.44	0.732	0.745
Tension at 767.8m from LC (kN)	0.304	0.309	0.515	0.517
Tension at 780.5m from LC (kN)	0.24	0.251	0.414	0.42
Tension at 805.5m from LC (kN)	0.145	0.156	0.253	0.259
Depth of TB (m)	46.75	46.65	34.34	34.28

References

[1] Holmstrom, J.T., 1982,“Custom designing winches for deep tow survey use”, Sea Technology, Vol 23, pp 10 - 12.

[2] Ketchman J.J and Lou, Y.K, Application of the finite element method to towed cable dynamics, Proceedings of Oceans, Marine Technological society, pp 98-107

[3] Albow C.M &Schechter.S, 1983, “Numerical simulation of undersea cable dynamics”, Ocean Engineering, Volume 10, pp 443-457

[4] Andrew R.N and Bull P.W, 1988, “Hydrodynamic behaviour of towed array sonar”, Journal of Naval Science, Vol 14, pp 188-198.

[5] Theodoracatos V.E and Calkins.D.E, 1986, “An experimental study of elastohydrodynamics of towed flexible cylinders aided by video image processing”, Ocean Engineering, vol 13, pp 587-619.

[6] D.A. Chapman, 1984, “Towed cable behaviour during ship turning manoeuvres”, Ocean Engineering, vol 11, pp327

[7] C.A Brebbia and S.Walker, “Dynamic analysis of offshore structures”, Butterworth and Co.Publishers Ltd.

[8] White.F., 1974, “An analysis of axi-symmetric turbulent flow past along cylinder”, Journal of Basic Engineering, pp 94,200-206

[9] Rao.G.N.V, 1967, “The law of wall in a thick axi-symmetric turbulent boundary layer”, Journal of Applied Mechanics, pp34,237-238

[10] Hansen.R.J and C.C.Ni,, 1979, “Flow induced transverse motions of a flexible cable aligned with the flow direction”, IEEEJ. Of Ocean Engineering. Vol 4, pp 152-156

[11] Kennedy R.M, 1987, “Forced vibration of a thin flexible cylinder in a viscous flow,” Journal of Sound and Vibration, pp 115,189-201

[12] Hoerner S.F, 1965, “Fluid Dynamic drag”, MIT Publication

[13] Berteaux H.O, 1972, “Buoy Engineering”, Wiley International science Publication

[14] Orcaflex8.7d Manual

[15] Mercier, Richard S.,Zhang, Jun, 2003, “Deep water mooring systems: concepts, design, analysis and materials”, Proceedings of the International Symposium